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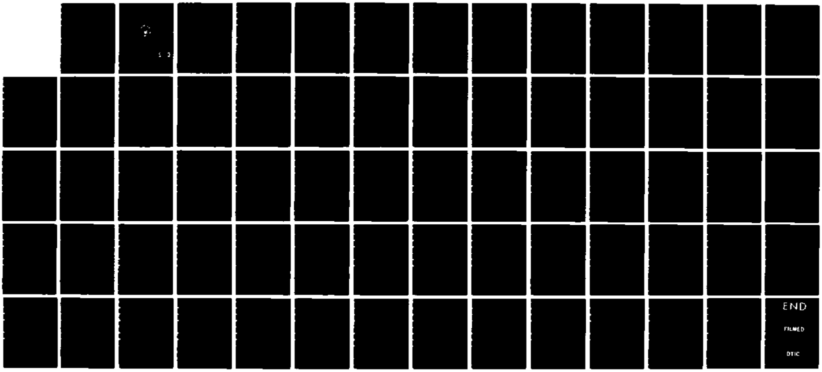

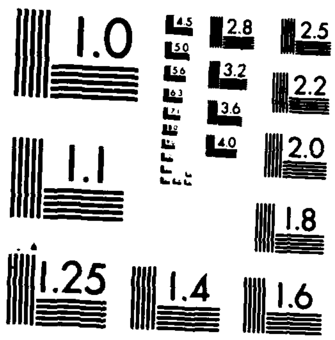

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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

WAVE AND SURF FORECAST MODEL EVALUATION
FOR USE ON A MICRO COMPUTER

by

Lee Earl Devendorf

June 1985

Thesis Advisor: E.B. Thornton

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Wave and Surf Forecast Model Evaluation for Use on a Micro Computer

by

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A sea swell and surf model is implemented, tested and evaluated on a micro computer (HP-9845B). The two-dimensional model includes spectral wind-wave generation in open water, and shallow water wave transformation over irregular topography. The model predicts surf zone width, breaker lines and types of breakers. Using change in momentum flux of gravity waves (radiation stress) as forcing, the model predicts current velocities within the surf zone. The model is evaluated for the conditions over constant depths and uniform sloping beaches. The numerical results are checked against accepted theory and field observations. The model is found to overbuild wind generated sea heights for a 30 kts wind but to give expected wave heights for a 15 kts wind. The model results compare well with observed nearshore wave heights but give poor location of breaking waves. The model's nearshore current calculation is found unsuitable for the HP-9845B due to computational instability and time requirements. The sources of the model's problems are identified, and recommendations are made for future improvements of the model.

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I. INTRODUCTION

A. MOTIVATION

Wave and surf forecasting is a primary concern of the U.S. Navy in executing amphibious operations. The wave environment affects the larger vessels in deep water and landing craft approaching the beach. As waves propagate from deep to shallow water, they undergo shoaling, refraction, and eventually breaking, while forming a surf zone. The height and type of breakers in the surf zone determines the difficulty that landing craft will have in reaching the beach. The breaking waves can also generate nearshore currents; these shear currents potentially can turn a craft and cause it to be broached and swamped by breaking waves. In addition to amphibious units, coastal structures and pierside ships are subject to forces by waves in shallow water regions.

The forecasting of wave conditions can be divided into two regimes: the nearshore, including the surf zone, and an offshore area. There are a number of numerical models available which predict waves, shear currents and surf conditions separately. Propagating wave energy from deep water to the high water line on the beach requires a combination of complementary models. The objective of this thesis is to convert a state-of-the-art computer program for use on a Hewlett-Packard 9845B mini computer, to test the model against field observations

and to revise where necessary. The program will be submitted as a prototype wave and surf model for shipboard use in the Fleet.

B. BACKGROUND OF WAVE AND SURF PREDICTION

The earliest models of wave generation and shallow water transformations were for monochromatic regular waves. Refraction was based on the wave ray method (Arthur, 1949), where ray paths were calculated for individual waves with slowly varying wave speeds along the wave front. This method is analogous to ray path prediction used in optics for light rays. With the development of computers and a better understanding of the physical processes, it became possible to consider the entire wave spectrum in generation and shallow water transformation. Karlsson (1969) introduced a direction variable to study wave spectral transformation for straight and parallel contours. Collins (1972) included bottom friction and evaluated the validity of one dimensional models. Noda, et al. (1974) used a relaxation finite-difference scheme to solve the stationary wave spectral transformation in shallow water with the inclusion of bottom dissipation and effects of local wind generation. Shiau and Wang (1977) studied wave transformation in shallow water and compared the results with field observations. Wang and Yang (1981) applied their model with the inclusion of bottom friction. Recently, Chen and Wang (1983) improved the model by considering non-stationary waves and interactions with currents.

C. CURRENT STATUS OF MODELING TECHNIQUE

The current state-of-the-art for numerical modeling can be characterized by two numerical methods, finite difference and finite elements. Both methods have been applied to wave and surf problems. A finite element model, such as by Wu and Liu (1985), economically handles localized irregular topography and has good properties for nonlinear convergence. However, finite element schemes are highly complex and require a sophisticated understanding of the model characteristics to choose the best grid system. Finite difference models (Noda, 1974; Shiau and Wang, 1977) use rectangular grids in general, and the numerical analysis has been widely studied. The numerical procedure of finite difference models is self-explained. Therefore, a finite difference scheme is less demanding on the user's numerical skills and from an operational point of view, is more practical.

D. MODEL OVERVIEW

The model described below was developed by Wang and Chen (1983). It is a finite difference model which considers a wind generated spectrum, spectral and swell wave transformations over moderately irregular bottom topography, and dissipation by breaking waves and bottom friction. The model calculates a wind generated and deep water wave spectrum in the ocean and predicts wave and surf conditions on the beach. There is also an option of direct input of a predetermined

wave into a surf area. In the nearshore computations, there are options for computing surf conditions and/or nearshore circulation. The surf and nearshore circulation output are the basis for predicting amphibious landing conditions. Model input includes wind direction and speed, initial ocean swell and dominating direction, bottom type, and water depths. All the inputs are entered for the deep water calculation and again serve as appropriate data for the shallow water.

E. OBJECTIVES

The objective of this thesis is to compile the numerical model by Wang and Chen (1983) in a user friendly version and test it on the HP-9845B mini computer. The program should be self-explanatory with internal error checks and simple correction steps. The model will be tested against observations on several beaches to establish accuracy and range of application. The physical and numerical limitations of the model will be documented, explained and where possible improved. It should be a useful tool for the Shipboard Aerographer Mates.

II. THEORY AND STRUCTURE OF THE MODEL

A. THE SEA SWELL AND SURF PROGRAM (SSSP)

The sea, swell and surf program (SSSP) was developed by Wang and Chen (1983) and is a combination of several complementary models. The sea and swell for open sea follows the models by Shiau and Wang (1977) and Chen and Wang (1982). The nearshore current calculation is based on a model by Birkemeier and Dalrymple (1976).

The version of the SSSP most suitable for use on the HP-9845B consists of a main program which controls nine subroutines. A flow chart of the program is given in Figure 1. The subroutine format of the SSSP allows for easier test and evaluation by component, modification or program correction, and reduced memory requirements on the mini computer. The main disadvantage of the subroutine format is some reduction in calculation speed.

B. REFRACTION OF SEA SWELL

The wave direction is determined using conservation of wavenumber for a steady state process (Phillips, 1977):

$$\frac{\partial(k \cos \theta)}{\partial y} - \frac{\partial(k \sin \theta)}{\partial x} = 0 \qquad (1)$$

where (x,y) are the on-offshore and alongshore directions, and θ is the counter clockwise angle from the X axis to the

m = bottom slope

H_o = deep water wave height

L_o = $1.56T^2$, deep water wave length

Breaker type is specified by the following criteria:

$$\varepsilon_b > 2 \text{ surging or collapsing}$$

$$0.4 < \varepsilon_b < 2 \text{ plunging}$$

$$\varepsilon_b < 0.4 \text{ spilling}$$

Effective surf is calculated in accordance with COMNAVSURFPAC/COMNAVSURFLANT Instruction 3840.1 for use in naval amphibious operations. "Effective surf height is a numerical value, expressed in feet, and provides a guide for judging the feasibility of landing operations for any given landing craft under existing or forecast conditions." Effective Surf is a function of:

1. Breaker Height
2. Breaker Period
3. Breaker Type
4. Littoral Current
5. Wind direction and velocity
6. Secondary wave height
7. Breaker angle

The parameters for the empirical calculation of effective surf are calculated in the surf condition part of the model except for littoral current. The nearshore current circulation in the model is described in the next section.

$$DBK = [(D_{I,J})(2-I) + (D_{I-1,J})(I-1)] + \left(\frac{D_{I,J}-D_{I-1,J}}{\Delta x}\right)X \tag{30}$$

where D is the bottom depth in the program.

Additional lines of breakers shoreward of the initial breaker are calculated by:

$$H_{b\ next} = \frac{b'\ d_{b\ next}}{1 + a'\ d_{b\ next}} \tag{31}$$

where

$$d_{b\ next} = h_{I,J} + \frac{h_{I+1,J} - h_{I,J}}{\Delta x}[X-(I-1)\Delta x] \tag{32}$$

The angle of the breaking wave (Angz) is calculated by interpolating the distance between grid points and the linear change in the wave direction:

$$Angz = Ang_{I,J} + \left(\frac{Ang_{I,J} - Ang_{I,J}}{X}\right)(X - (I-1)\Delta x) \tag{33}$$

where Ang is the calculated wave direction at the grid point.

The type of breaker is based on the surf parameter:

$$\varepsilon_b = \frac{m}{(H_o/L_o)^{1/2}} \tag{34}$$

where:

The coefficients c, d, e and f are determined by using standard slope intercept techniques. The positive root of this quadratic equation is the width of the surf zone.

$$a(m) = 1.36(1 - e^{-19m}) \tag{27}$$

$$b(m) = \frac{1.56}{1 + e^{-19.5m}} \tag{28}$$

$$a' = \frac{a(m)}{T^2}$$

$$b' = b(m)$$

where:

m = bottom slope between grid points

The first breaking wave height, denoted as HBK in the program, is then determined using the surf zone width by interpolating between grids.

$$HBK = ((H_{I,J}((2-I) + (H_{I-1,J})(I-1)) + (\frac{H_{I,J} - H_{I-1,J}}{\Delta x})X \tag{29}$$

where H is the original wave height from energy considerations only and I and I-1 are the grids that bracket the deepest breaker in the on-offshore direction.

The depth of the first breaker, DBK, is calculated also using the surf zone width and the interpolation between grids:

height and period. Initial wave height and direction are determined for the entire model grid using swell direction and wave height calculations described in Chapter II, sections B and C. The depth of the first breaker is determined by comparing the calculated wave height with the incipient breaking criteria (Noda et al., 1974; Thornton and Guza, 1983).

$$\frac{H_b}{L} = 0.43 \operatorname{Tanh}\left(\frac{d_b}{L}\right) \qquad (25)$$

The width of the surf zone, X_b, is then calculated using the relationship between breaker height, breaker depth, wave period, and bottom slope (Weggel, 1972).

$$\frac{H_b(x)}{d_b(x)} = b(m) - a(m)\,\frac{H_b(x)}{T^2} \qquad (26)$$

assuming

$$H_b(x) = c + dX_b \qquad (26a)$$

$$d_b(x) = e + fX_b \qquad (26b)$$

Solve:

$$(a'bf)X_b^2 + (a'ed + a'cf - b'f + d)X_b + (a'ce + c - b'e) = 0 \qquad (26c)$$

expression for a frequency-dependent dissipation function:

$$\varepsilon_d(f) = \rho\ c_f|\vec{U}_b|\ u_b(f) \tag{22}$$

where c_f is a bed shear stress coefficient, $u_b(f)$ is the wave induced bottom velocity at a particular spectral component, and U_b is the bottom velocity for the total flow field. Applying linear wave theory transfer functions relation the energy spectrum of the surface elevation to the velocity field, (22) can be expressed as:

$$\varepsilon_d(f) = \rho c_f[\frac{g^2 k^2}{\sigma^2 \cosh^2(kd)}]S(f)U_b \tag{23}$$

where the term in the brackets is the spectral transfer function. The total bottom velocity is obtained by applying the spectral transfer function to the entire spectrum:

$$(U_b) = [\int_0^{\infty} \frac{g^2 k^2 S(f)}{\sigma^2 \cosh^2 kd}\, df]^{1/2} \tag{24}$$

D. THE SURF MODEL

This model describes the surf zone width, number of lines of breakers, breaker type, breaker angle, significant and maximum breaker height, and the effective surf. The calculations are based on empirical formula given in the Shore Protection Manual (U.S. Corps of Engineers, 1977). The input wave is monochromatic, and requires only significant wave

and

$$W_n = \sigma\left(\frac{d}{g}\right)^{1/2} \qquad (18)$$

where

$$\Sigma(W_n)$$

satisfies the condition

$$\Sigma \; \mathrm{Tanh}(W_n \Sigma) = 1 \qquad (19)$$

$\Gamma(W_n) = 1$ in deep water, and for W_n less than 1,

$$\Gamma(W_n) \simeq \frac{1}{2} W_n^2 \qquad (20)$$

and

$$S(f,\delta) = \frac{1}{2} q g d f^{-3} H(\delta) \qquad (21)$$

where q is a coefficient on the order of 10^{-2}; a value of .073 is used in Wang's model.

The bottom dissipation term, ε_d, is due to work done on the bottom by the bed shear stress. The bed shear stress is proportional to velocity squared and the rate of energy dissipation is proportional to the cube of the velocity. Hasselman and Collins (1968) proposed a quasi-linearized

$$S_m = \rho g \beta [S(f)] \qquad (12)$$

where:

$$\beta = \frac{As\sigma}{2\pi}\left[\frac{W \cos \delta}{c} - B\right] \qquad (13)$$

s = ratio of air to water density

A = 5

B = .9

The wind wave generation is then the sum of (S_p) and (S_m):

$$\varepsilon_s = S_p + S_m \qquad (14)$$

The wave growth is limited to a fully risen sea at each spectral band. The limits on development are based on Phillips (1957) equilibrium spectrum modified by Kitaigorodskii et al (1975) and Thornton (1977) for the shallow water condition:

$$S(f,\delta) = B\, g^2 f^{-5} H(\delta)\Gamma(W_n) \qquad (15)$$

where:

$$H(\delta) = \left(\frac{8}{3\pi}\right)(\cos^4(\delta)) \qquad (16)$$

accounts for angular spreading,

$$\Gamma(W_n) = \Sigma^{-2}(W_n)\left\{1 + \frac{2W_n^2\Sigma(W_n)}{\sinh[2W_n^2\Sigma(W_n)}\right\}^{-1} \qquad (17)$$

Barnett (1968) fitted the following empirical relationship for P based on field measurements:

$$P(k,\sigma) = \frac{6.13 \times 10^{-4} w^6}{\pi^2 \sigma^2} \left[\frac{\nu_2}{\nu_2^2 + (k \sin \delta)^2}\right] \cdot \left[\frac{\nu_1}{\nu_1^2 + (k \cos \delta - \Lambda)^2}\right] \qquad (11)$$

where:

δ = angle between wind and wave

w = wind speed (meters/second)

Λ = σ/w

ν_1 = $0.3^{1.28}$

ν_2 = $0.52^{0.95}$

This mechanism is important for wave initiation from calm water and results in a linear increase in energy with time (Hasselman, 1960).

The Miles energy transfer mechanism is important only after waves have formed (LaBlond and Mysak, 1978). When wind blows over an irregular sea surface, flow separation can occur in the lee of the wave crest creating pressure differences. Momentum is transferred to the waves as a result of these pressure forces. The instability mechanism of Miles' results in exponential wave growth (Barnett (1968); Hasselmann (1960)).

$$\rho\ g\ \frac{\partial}{\partial x}(S(f)\ C_g \cos\ \overline{\theta}) + \rho\ g\ \frac{\partial}{\partial y}(S(f) C_g \sin\ \overline{\theta})$$

$$= -\ \varepsilon_d(f) + \varepsilon_s(f) \qquad (7)$$

where:

$S(f)$ = wave energy density at spectral frequency f

ρ = density of the fluid

g = acceleration due to gravity

$\varepsilon_d(f)$ = energy dissipation through bottom friction

$\varepsilon_s(f)$ = energy generation due to wind stress

The energy generation term, ε_s, is based on the mechanisms used for wind energy transferred to the wave field described by Phillips (1957) and Miles (1957;1959a,b;1962). The Phillips mechanism is due to random atmospheric pressure fluctuations advected by wind resonantly interacting with a perturbed sea surface. The wave energy generated by the Phillips wind mechanism is

$$S_p = \rho\ g \alpha \qquad (8)$$

where

$$\alpha = \frac{4\pi^2\ k \alpha_1^3}{\rho^2 g^3} P(k,\sigma) \qquad (9)$$

and

$$\alpha_1 = \sigma/g \qquad (10)$$

C. WAVE HEIGHT TRANSFORMATION

The information of wave direction is used to calculate an initial guess for the energy field. The initial energy at each grid point is calculated by assuming conservation of energy over straight and parallel contours.

$$\frac{\partial(E\ C_g\ \cos\ \theta)}{\partial x} = 0 \tag{5}$$

Integrating (5) leads to the initial energy field:

$$E = E_o \frac{C_{go}}{C_g} \frac{\cos\ \theta_o}{\cos\ \theta} \tag{6}$$

where the subscript (o) refers to conditions at the offshore boundary and C_g is the group velocity. The initial guess energy field is used to calculate the wave height field.

The calculation of wave height is based on the energy balance equation including refraction, dissipation and growth. Three assumptions are made to speed calculation and reduce model complexity (Chen and Wang, 1983). First, it is assumed that wave energy within a particular spectral band stays in that band, which allows linear superposition of wavelets. The second assumption is that each frequency component can be described by a single mean direction, $\overline{\theta}$. Third, it is assumed that there are no wave-current interaction. With these assumptions, the steady state energy flux equation for each spectral band can be written (Longuet-Higgins, and Stewart, 1960, 1962).

The wave number $k_{i,j}$ is the positive root of the linear wave dispersion relationship

$$\sigma = (g\,k \tanh kd)^{1/2} \qquad (3)$$

where d is the water depth and σ is the angular frequency. In the original SSSP model by Wang and Chen (1983), the wave-number was solved for in (3) using an iterative Newton's method. However, to speed up the model, the wavenumber is calculated here using a 6th degree polynomial fit of (3) as given by Hunt (1979):

$$\begin{aligned} k = \frac{\sigma}{\sqrt{gd}}(S + (1 &+ 0.66667S + 0.35550S^2 \\ &+ 0.16084S^3 + 0.06320S^4 + 0.02174S^5 \\ &+ 0.00654S^6 + 0.00171S^7 + 0.00039S^8 \\ &+ 0.00011S^9)^{-1})^{-1} \end{aligned} \qquad (4)$$

where:

$$S = \sigma^2(d/g)$$

This non-iterative approximation resulted in an observed 90 percent savings in computation time on the HP-9845B with the same accuracy.

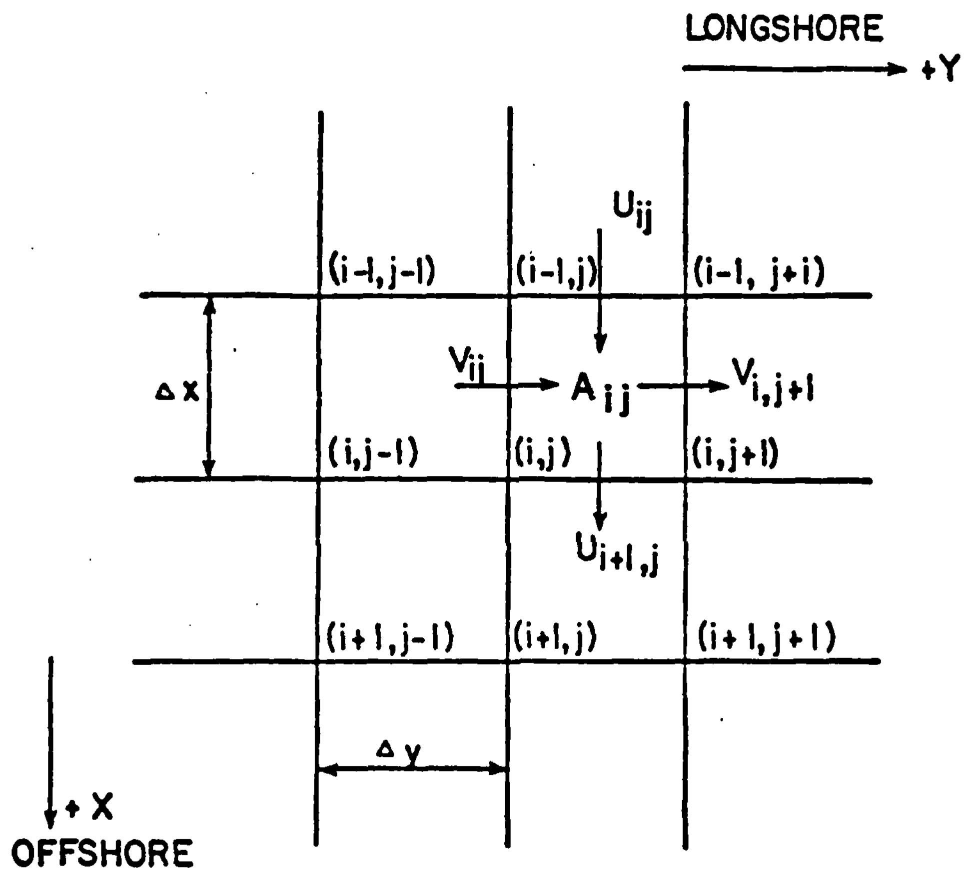

Figure 2. Differencing scheme used in the model. The grid points are identified by subscripts with the first subscript indicating position from the beach with increasing numbers farther offshore. The second subscript indicates position alongshore with increasing numbers to the right when the beach is viewed from a ship off the coast.

direction of swell propagation and k is the wavenumber. It is assumed that (1) is valid in both open water and within the surf zone.

Noda (1972) developed an iterative scheme to solve (1) for the wave angle. The convention for grid location of the numerical model is shown in Figure 2. The differential equation is central-differenced in the X-direction and forwarded-differenced in the Y-direction. The finite difference form of the equation used by Noda (1972) with weighting on the forward difference term added to increase stability (after Abbot, 1979) is used here:

$$\theta_{i,j} = \sin^{-1}\{\frac{1}{k_{i,j}}[(\tau)(k \sin \theta)_{i+1,j-1} - (1 - 2\tau)(k \sin \theta)_{i+1,j} + (\tau)(k \sin \theta)_{i+1,j+1} - \frac{\Delta x}{2\Delta y}((k \cos \theta)_{i,j+1} - (k \cos \theta)_{i,j-1})]\} \quad (2)$$

where weighting factor of $\tau = 0.25$ is used. The initial guess for the wave angle is calculated by applying Snell's law for parallel bottom contours. (This gives an exact solution in the case of a plane sloping beach.) The initial guess field of $\theta_{i,j}$ is iterated until $\theta_{i,j}$ is within a half percent of the previous iteration.

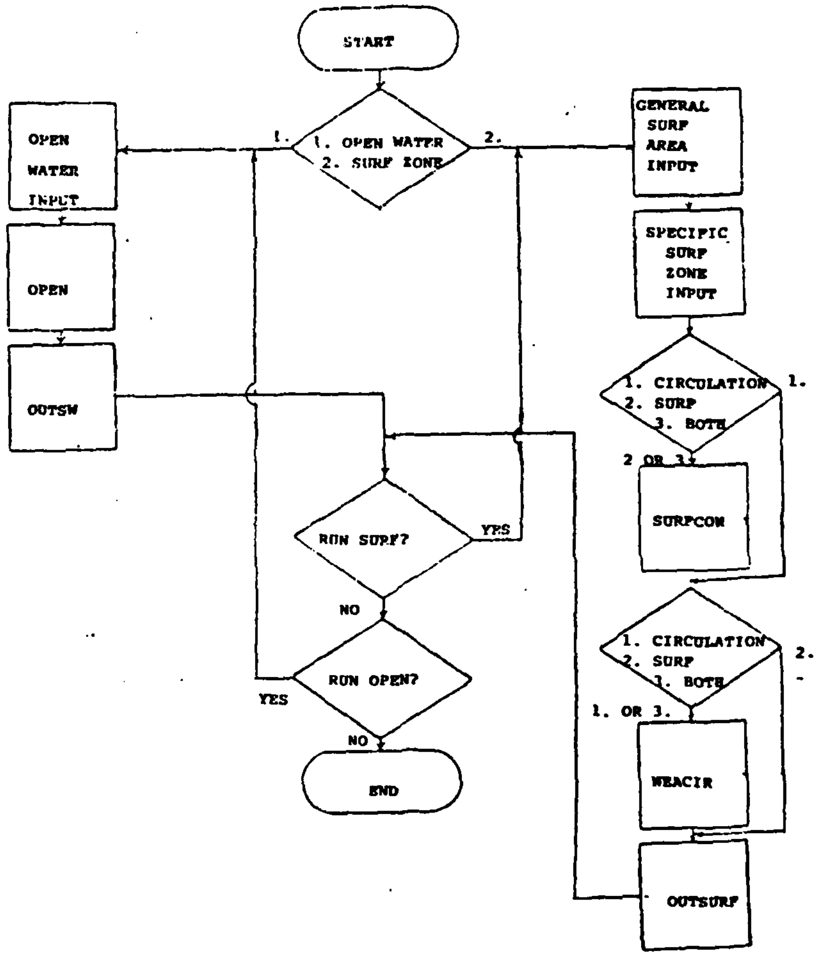

Figure 1. Sea Surf and Swell

E. NEARSHORE CIRCULATION MODEL

The nearshore circulation is generated by changes in momentum due to breaking waves within the surf zone and by wind induced surface stress. The nearshore circulation model is based on the depth integrated and time averaged equations of motion by Phillips (1977). The breaking wave-induced currents are calculated by alternately solving the momentum and the continuity equations. The equations are solved numerically with the finite differences scheme taken directly from Kirby and Dalrymple (1982) which is an updated version of Birkermeier and Dalrymple (1977). The x and y momentum equations are integrated over the depth and time averaged over one or several wave periods. The equations contain bottom shear stress, mean surface shear stress and excess mean momentum stress due to wave action. To simplify the model, the formulation neglects the nonlinear mean momentum flux terms and the lateral (horizontal) transfer of turbulent momentum. The continuity equation is given by:

$$\frac{\partial \bar{\eta}}{\partial t} + \frac{\partial}{\partial x}[\bar{u}(d + \bar{\eta})] + \frac{\partial}{\partial y}[\bar{v}(d + \bar{\eta})] = 0 \qquad (35)$$

where $\bar{\eta}$ is the free surface elevation, d is the still water depth, (u,v) are the (x,y) horizontal velocity components and the overbar indicates time averaging. The horizontal momentum equations are

$$\frac{\partial \bar{u}}{\partial t} = - g \frac{\partial \bar{\eta}}{\partial t} - \frac{1}{\rho(d+\bar{\eta})}\left(\frac{\partial S_{xx}}{\partial x} + \frac{\partial S_{xy}}{\partial y} - \bar{\tau}_{sx} + \bar{\tau}_{bx}\right) \qquad (36)$$

$$\frac{\partial \bar{v}}{\partial t} = -g\frac{\partial \bar{\eta}}{\partial y} - \frac{1}{\rho(d+\bar{\eta})}\left(\frac{\partial S_{yx}}{\partial x} + \frac{\partial S_{yy}}{\partial y} - \bar{\tau}_{sy} + \bar{\tau}_{by}\right) \tag{37}$$

The S_{xx}, S_{xy}, S_{yx}, S_{yy} are the mean momentum flux due to the wave motion (commonly referred to as radiation stresses). τ_{sx}, τ_{sy} are the surface shear stresses due to wind, and τ_{bx}, τ_{by} are the bottom stresses.

The radiation stresses are given by (Longuet-Higgins and Stewart, 1964):

$$S_{xx} = E[(2n - 1/2)\cos^2\theta + (n - 1/2)\sin^2\theta] \tag{38}$$

$$S_{yy} = E[(2n - 1/2)\sin^2\theta + (n - 1/2)\cos^2\theta] \tag{39}$$

$$S_{xy} = S_{yx} = \frac{E}{2}n\sin(2\theta) \tag{40}$$

where E is wave energy $= \frac{1}{8}\rho g H^2$; $n = C_g/C$.

The surface wind shear stresses are calculated (Van Dorn, 1953) by:

$$\bar{\tau}_{sx} = \rho K|W|W_x \tag{41}$$

$$\tau_{sy} = \rho K|W|W_y \tag{42}$$

where W_x, W_y are the wind speed in the (x,y) directions, and K is the wind stress coefficient of order 10^{-6}.

The bottom shear stresses are linearized by assuming weak mean currents (U,V) (LaBlond and Mysak, 1978).

$$\overline{\tau}_{bx} = \rho \frac{4}{\pi} c_f u_m U \tag{43}$$

$$\overline{\tau}_{by} = \rho \frac{2}{\pi} c_f u_m V \tag{44}$$

where c_f is the Darcy-Weisbach bottom friction factor and u_m is the maximum wave orbital velocity at the bed:

$$u_m = \frac{H\,\sigma}{2 \sinh kd} \tag{45}$$

The maximum time step Δt is based on the linear stability criterion (Kirby and Dalrymple, 1982):

$$\Delta t \leq \sqrt{((\Delta x)^2 + (\Delta y)^2/2gd)} \tag{46}$$

However, in practice, Kirby and Dalrymple (1982) recommend using a quarter of this value. The actual Δt used in the program is

$$\Delta t = \frac{1}{3} \frac{(\Delta x^2 + \Delta y^2)^{1/2}}{(gd)^{1/2}} \tag{47}$$

The finite difference form of (36) and (37) are given by:

$$U_{new_{I,J}} = U_{old_{I,J}} + \Delta t[(\eta_{I-1,J} - \eta_{I,J})\frac{g}{\Delta x} + (\frac{S_{xx_{I-1,J}} - S_{xx_{I,J}}}{\Delta x \rho d})$$

$$- (\frac{S_{xy_{I,J+1}} - S_{xy_{I,J-1}} + S_{xy_{I-1,J+1}}}{4\Delta y \rho d} - \frac{S_{xy_{I-1,J-1}}}{4\Delta y \rho d})$$

$$+ (\frac{\tau_{sx_{I,J}} + \tau_{sx_{I-1,J}}}{2\rho d}) - (\frac{\tau_{bx_{I,J}} + \tau_{bx_{I-1,J}}}{2\rho d})] \qquad (48)$$

where:

$$d = (\frac{d_{I,J-1} + d_{I-1,J-1}}{2})$$ is the average depth in the X-direction

$$V_{new_{I,J}} = V_{old_{I,J}} + \Delta t[(\eta_{I,J-1} - \eta_{I,J}) \frac{g}{\Delta y}$$

$$- (\frac{S_{xy_{I+1,J-1}} - S_{xy_{I-1,J-1}}}{4\Delta x \rho d}) - (\frac{S_{xy_{I+1,J}} - S_{xy_{I-1,J}}}{4\Delta x \rho d})$$

$$+ (\frac{S_{yy_{I,J-1}} - S_{yy_{I,J}}}{\Delta y \rho d}) + (\frac{\tau_{sy_{I,J}} + \tau_{sy_{I,J-1}}}{2\rho d})$$

$$- (\frac{\tau_{by_{I,J}} + \tau_{by_{I,J-1}}}{2\rho d})] \qquad (49)$$

where:

$$d = (\frac{d_{I,J-1} + d_{I,J-2}}{2})$$

The finite difference form of (35) solving for $\overline{\eta}$ is

$$\overline{\eta}_{new_{I,J}} = \overline{\eta}_{old_{I,J}} + \Delta t[U_{I,J}(\frac{d_{I,J-1} + d_{I-1,J-1}}{2\Delta x})$$

$$- U_{I+1,J}(\frac{d_{I,J-1} + d_{I+1,J-1}}{2\Delta x}) + V_{I,J}(\frac{d_{I,J-2}+d_{I,J-1}}{2\Delta y})$$

$$- V_{I,J+1}(\frac{d_{I,J} + d_{I,J-1}}{2\Delta y})] \qquad (50)$$

The new water depth is then given by:

$$d_{I,J} = (d_{I,J} - \overline{\eta}_{I,J})^{old} + \overline{\eta}^{new}_{I,J}$$

The nearshore circulation solutions are "spun up" to steady-state condition. The model is started from state of rest with zero wave field present (Kirby and Dalrymple, 1982). To reduce the effect of seiching or instability, the wave height H at the offshore grid is gradually brought up to its full value using:

$$H = H_o \tanh(\frac{2t}{T_s}) \qquad (51)$$

where:

t = model time

T_s = arbitrary fixed period

H_o = full height of boundary wave

The hyperbolic tangent function is used to control the growth of the boundary wave during an iterative process. The quantity $[2t/T_s]$ increases linearly while the tanh function increases smoothly toward unity.

III. MODEL APPLICATION ON THE HEWLETT-PACKARD 9845B

A. CONVERSION INTO BASIC

The U.S. Navy contracted for the development of the wave and surf model which was written in FORTRAN. In its original form, the model was written for a large non-portable computer. To make the model useful tactically for mobile U.S. Navy forces, the program is rewritten specifically for deployed micro computers like the HP-9845B. It is required that the model be written in a user friendly format with common naval conventions and terms. Error checking and input review had to be programmed into the model to be operationally acceptable to the U.S. Navy. The Wave and Surf Model had to run on the HP-9845B to give reliable, useful and easily understood output.

B. MODIFICATIONS IN THE WAVE AND SURF MODEL FOR THE HP-9845B

The original contractor delivered a FORTRAN version of the wave and surf model written in a format of "stand alone subroutines." This version was suitable for conversion to the HP-9845B because its size was within the micro computer's memory requirements. The subroutine format also allowed for easier testing of the model. The main change made in the program involved the use of common statements. The FORTRAN version made extensive use of labeled common blocks. The HP basic only allows one common statement. This minor problem

was solved by increasing the size of variables in the call statement to most subroutines. Only the most often used general variables were used in the single common statement.

The language of the input statements is changed to agree with naval conventions. Wind and swell are described by the direction they arrive from. The beach is described from the point of view of a ship offshore.

The interactive subroutines are expanded with lines of code that:

1) explain the input needed
2) ask for the data input
3) error check the data input before accepting or rejecting and requesting correct input.

The program was expanded in the calculation code with explicitly assigned variables for counters and matrices. For example, effective surf was stored into a unique array rather than sharing an array used for several other calculations. Empirical values from the COMNAVSURFPAC/COMNAVSURFLANT Instruction 3840.1 were put into an array rather than use the FORTRAN version data fitting calculation. The additional memory space for these arrays was traded for explicitly assigned data and clearer programming.

Labels were placed before every significant calculation in the model code. Spaces were added between code to separate functional groups. Indentations of the code were made to show loops and double loops. These changes added to the readability of the program and made the model logic easier to follow.

In addition, changes/corrections were made to the sea surf and swell model for undefined constants, incorrectly dimensioned arrays, logic errors and improperly defined angles. Some of these changes were made with the cooperation of the contractor. In the program code, each change is documented.

IV. DISCUSSION

A. USABILITY

The sea, surf and swell model is programed to be interactive in language a sailor can understand. The units for wave height and bottom depth entires can be either meters or feet. Grid spacing can be in nautical miles only for the open water version. However, the nearshore model allows either feet or meters. All entries are requested with a format example. Where possible, the format example is in standard World Meteorological Organization code, which should be familiar to all U.S. Navy Aerographers Mates. Suggested input values, or default values, are offered where appropriate to make the model more "user friendly."

B. DATA INPUT REQUIREMENTS

The quality of the input data is the most important factor determining accurate wave and surf forecasts. The bathymetry begins to affect sea and swell when the depth is less than half a wave length. For the same depth of water, the effect of the bottom will be strongest on longer period waves. The more shallow the water, the greater the effect will be on all waves. Accurate bathymetric data is needed in deeper sections of the model grid, but becomes increasingly important for shallow waters. The wave period and depth is used to compute

wavelength and phase speed. These parameters determine forecast wave direction, energy, surf type and currents generated in the surf zone. For the same reason, initial wave direction is as important as the wind direction. The bottom type input influences energy dissipation and surf zone currents. The surf model calculation is least sensitive to the bottom type.

The most difficult, and clearly the most important input, is the offshore wave input. Careful consideration must be given to the many sources of deep water waves. The open model sums the energy from all deep water wave inputs. The wave spectrum input must be accurately described. The ocean can be nearly flat concealing long period swell that can generate catastrophic surf on beaches. The ocean can have fully developed seas generated by continuous wind. In a fully developed sea, the energy of the waves is distributed over a wide range of periods that must be entered into the model for accurate surf forecasts. Only with a sound knowledge of deep water wave conditions can the model be used to forecast shallow water conditions.

The open water part of the model has the most options for wave energy input, which include:

1. A single narrow band swell.
2. A significant wave height and period which can be expanded in terms of a Bretschneider spectrum.
3. Specific energy levels can be entered at appropriate frequencies such as from the Navy Spectral Ocean Wave Model.

It is important to note that the output from this model is a single significant wave height and period moving in the direction of maximum energy. This could be a poor representation if the seas were large and from diverse directions.

The surf and nearshore circulation parts of the model allow only a monochromatic wave input. This input could be directly from the open water calculation or an input of the user's choice. If there is more than one dominant wave group approaching the beach, the model representation of the surf zone will be incomplete.

C. SELECTING THE GRID SIZE

The grid size and the distance between grid points will determine the model's ability to resolve the wave climate. The open water model has grid distances in nautical miles. The grid mesh should cover the area from deep water waves into shallow water, outside the surf zone. The grid size for the surf and nearshore is measured in feet, and the selection is critical to resolving the surf zone. Kirby and Dalrymple (1982) outline the following requirements for the nearshore circulation grid.

1. The grid must extend offshore far enough to remove the offshore region of the domain from the influence of currents driven by the surf zone, and to allow for the specification of a uniform longshore depth which will not significantly alter the wave refraction results in the nearshore.

2. The grid mesh must be fine enough to resolve the surf zone adequately.

3. In the event that the effect of a single physical feature isolated in the longshore direction is to be

> modeled, the longshore extent of the grid must be sufficiently large to isolate the physical system from the effect of images created by the longshore periodicity requirement.

Experience running the model suggests that a minimum of 3 grid points must be inside the surf zone. This would not be possible for waves breaking directly on the beach. A further constraint is the number of grids in this model (10 offshore rows and 13 columns alongshore) due to the limitations of speed and storage area of the micro computer.

V. MODEL TEST AND EVALUATION

A. DEEP WATER WIND GENERATED WAVES COMPARED WITH JONSWAP CURVES

The model approximates the area under the spectral density curve (wave energy) with rectangles. The more rectangles used, the better the approximation will be, but computational time also increases. The open water model requires approximately 45 minutes to calculate each frequency band on the HP-9845B. Narrow band swell waves might be closely approximated with a single energy band and a band width of .01 Hz. A broad band wave spectrum, such as wind waves, needs to be represented by multiple energy bands.

To test the wind generation model and the effects of bottom friction and band width selection, the model was run for constant depths of 100, 10, and 5 meters (Figs. 3, 4, and 5). The initial wave height is zero. The bottom friction coefficient chosen is .01 for a fine sand bottom. The grid spacing is 10 nautical miles resulting in a maximum fetch of 90 nautical miles. The results are compared with the JONSWAP significant wave height as a function of fetch from Bishop (1983). The model results favorably agree with the JONSWAP curve considering the relative coarseness of the energy bands. For the 100 m depths, bed friction was insignificant in changing the wave height as expected.

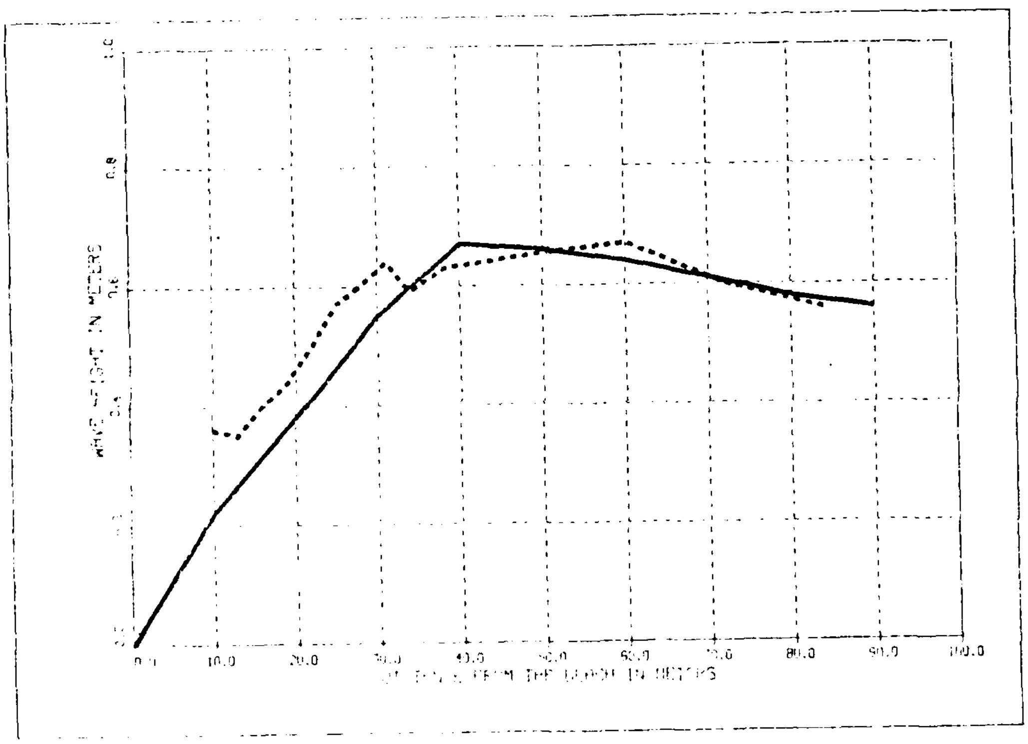

Figure 10. Santa Barbara surf zone wave height on 4 February 1980. Model computed values are represented by the solid line, observed heights are dashed.

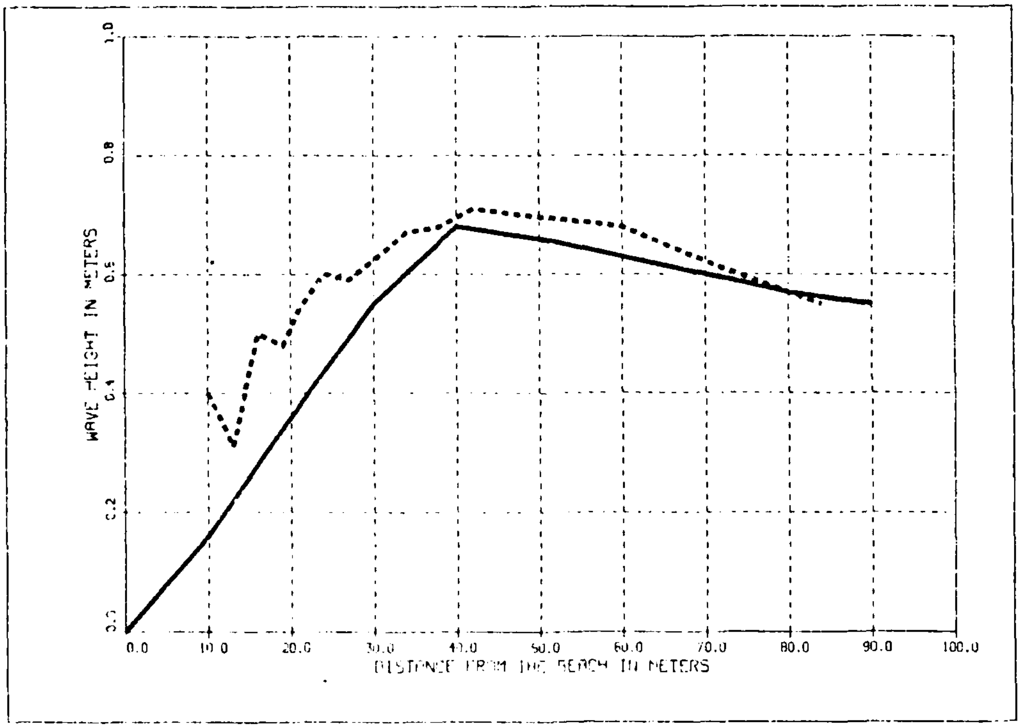

Figure 9. Santa Barbara surf zone wave height on 3 February 1980. Model computed values are represented by the solid line, observed heights are dashed.

TABLE I

Offshore Boundary Conditions

Date	Depth (m)	H_{rms} (m)	T (sec)	Wave direction (°)
Santa Barbara, Leadbetter Beach, California				
3 Feb 80	4.1	.55	14.3	-7.8
4 Feb 80	4.2	.56	14.3	-9.0
5 Feb 80	4.1	.45	12.8	-8.4
Torrey Pines Beach, California				
4 Nov 78	6.7	.35	14.3	0
10 Nov 78	6.6	.68	15.9	0

of the current became large and changed sign. The surf model is very slow to converge to a solution and unstable for even slightly longer time steps.

C. SURF CONDITION

The surf zone wave heights and directions calculated by the model were compared with observations. The comparisons were made with observations for two California beaches at Santa Barbara and Torrey Pines. These beaches are nearly plain sloping. The offshore boundary condition of wave height, period and direction are given in Table I. The beach material for the model friction coefficient selection was fine sand (Cf = .01). The modeled and observed wave direction agreed, within round-off, to the nearest degree for all days. The waves turned toward normal while crossing the surf zone exactly as expected.

Model comparisons for observations on 3 February are shown in Figure (9) which shows the model slightly under-predicts the wave heights but follows the general change across the surf zone. The breaker line was forecast to be 14.9 meters from the shore with a height of .68 meters. The observed breakers began more than 40 meters from the beach with a height of .68 meters. The model incorrectly forecast one line of breakers when at least two were observed.

The 4 February results (Figure (10)) show reasonable prediction of wave height. But using the wave height information, the model did not predict the location or height

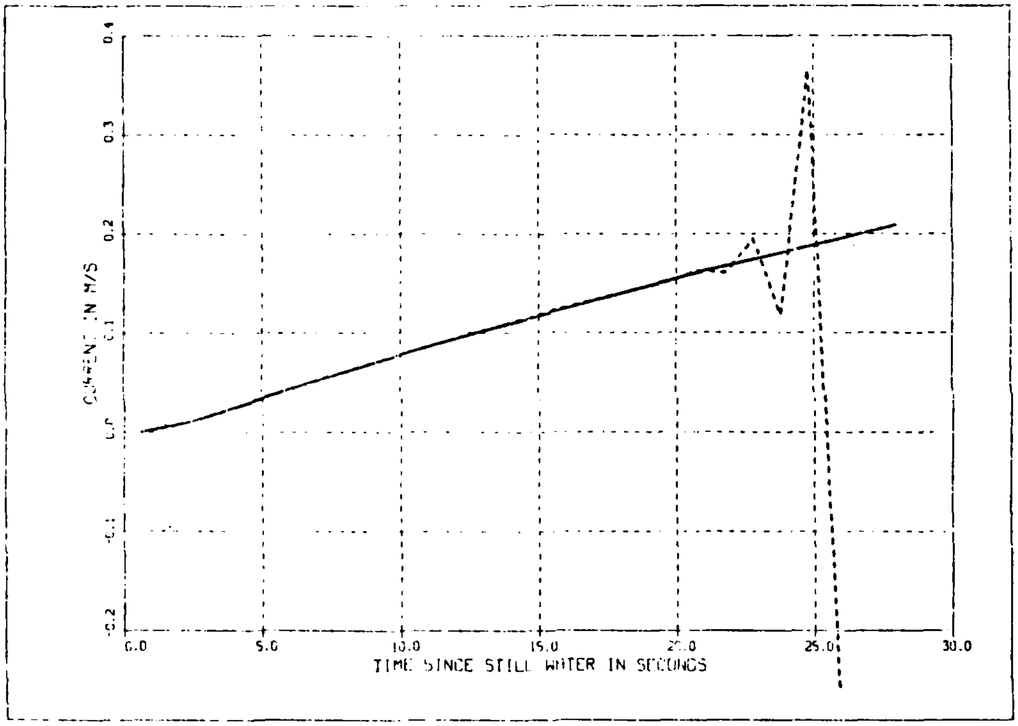

Figure 8. Surf zone current modeled for 4 Feb 1980 off Santa Barbara, California. The stable increase in current is shown with the solid line. The unstable calculation is shown with the heavy dashed line.

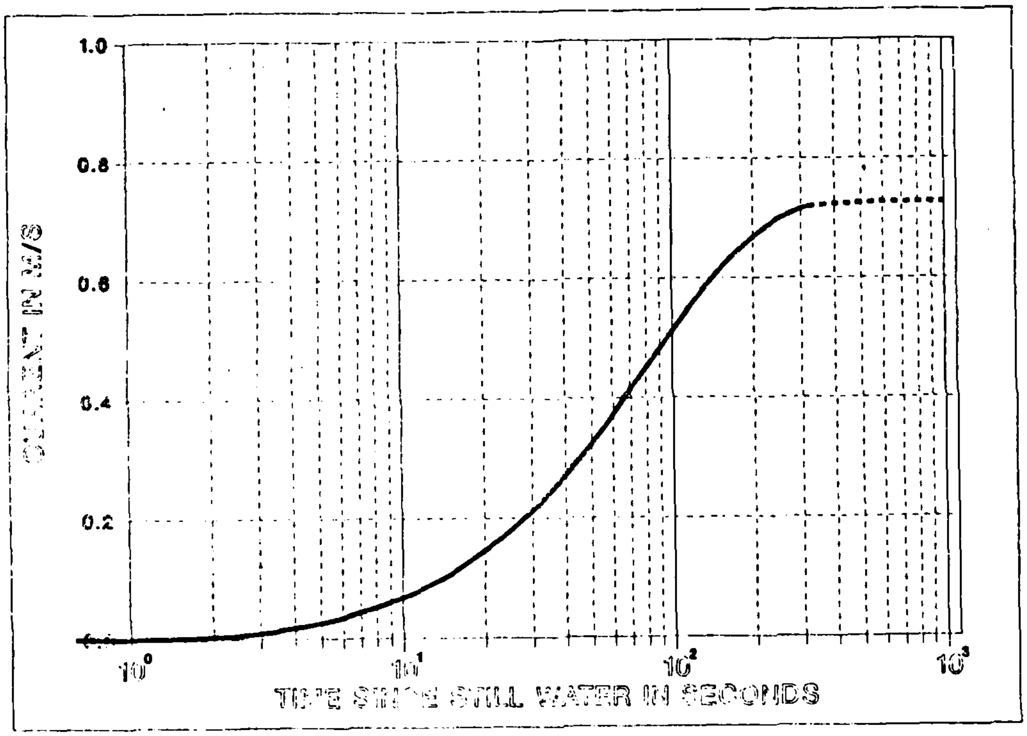

Figure 7. Current generated by the surf as predicted by the model as a function of "spin up" time. A total of 381 time steps were made representing 316 seconds of forcing by the surf. The dashed line is an extrapolation of the model's calculation.

depth of zero (at the beach presumably). The surf zone for this test was closer to the beach than $2\Delta x$ or 20 meters.

3. The changes in radiation stress, which forces the current, were very small across the breaker line where it should be the largest. The current would remain too small even with items 1 and 2 corrected due to weak forcing. Realistic radiation stress was not being calculated because the model gave incorrect wave heights for breaking in the surf zone. This correction was made.

The model was run again for comparison with Santa Barbara data. The grid size was reduced to $\Delta x = 2.5$ meters and $\Delta y = 5$ m. The time step for this small grid was approximately .6 seconds. The HP-9845B was allowed to calculate for 381 time steps which took 9 hours. This calculation represented 5.28 minutes real time for waves entering still water. The maximum stable time step is a function of the grid size

$$\text{TMAX} = 1/3 \frac{\Delta x}{gd}$$

The current was approaching a steady state with a very slow rate of convergence (Fig. 7). It would take more than 23 hours of CPU time on the HP-9845B to run the model for a 1000 steps as done by Kirby and Dalrymple (1983). Attempts to increase the time step and decrease the CPU time resulted in numerical instability (Figure 8). The model was run using the same input except the Δt was increased 5 percent each time step until reaching a maximum of one second. Instability began to occur after 20 seconds with values oscillating around the stable solutions. After 25 seconds the unstable model

uniform in the Y direction. The calculated wave directions were constant in the Y direction, the wave height and surf changed a few percent but the variations of current and wave set-up in the Y direction deviate more than 20 percent. The wave height and surf were slightly inconsistent with expected results and this is thought to be caused by the finite differencing scheme producing errors from the boundaries. The larger variation in the current and wave set-up values is probably due to the inconsistent mass flux calculations. The boundary errors induced in the wave calculations resulted in a nonuniform forcing term, and, therefore, they may not be able to describe a constant current. The model is expected to give best results in the interior of the computational domain for wave and surf prediction.

The nearshore current calculation portion of the model was compared with data acquired at Santa Barbara on 4 February 1980. Initially the currents calculated were one order of magnitude smaller than the observations.

Consequently, three basic problems with the surf model were identified:

1. The model computed only 36 seconds of surf after beginning with still water. The contractor's program calculated only 10 time steps, or 3.6 seconds. This length of time was too short to even approach a steady state current. Kirby and Dalrymple (1982) always ran their nearly identical version of this model for a 1000 time steps representing more than 5 minutes real time.

2. The resolution was too coarse to describe the current field. The finite difference scheme is unable to compute currents nearer than 2 gird spaces from a

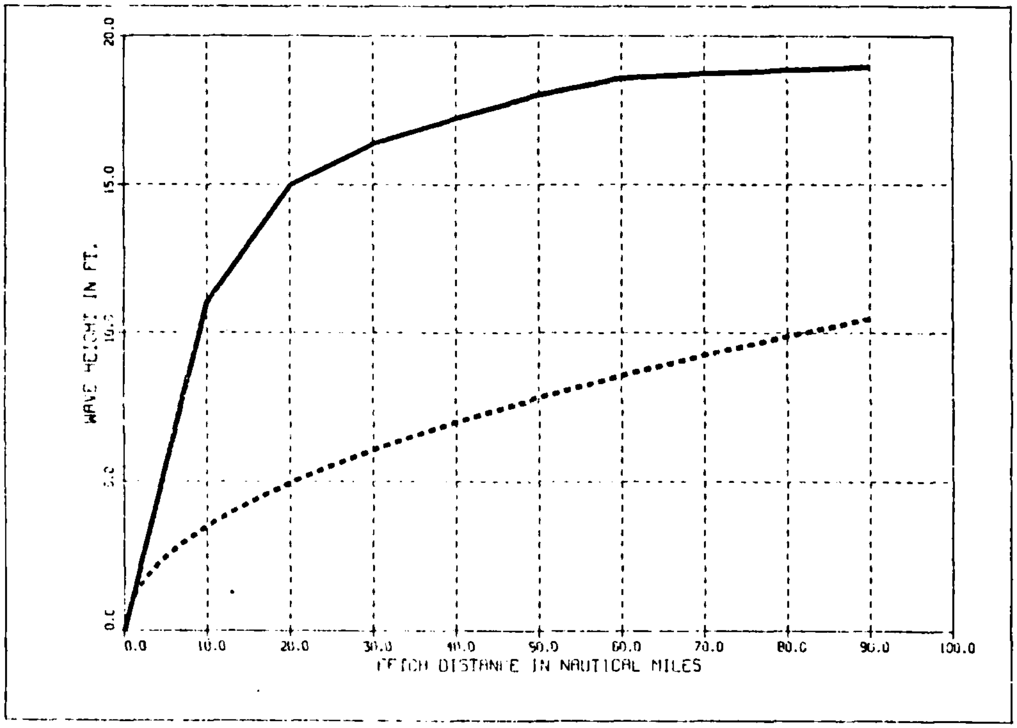

Figure 6. Significant wave height generated by a 30 kt wind in 100 meter water depth. Model computed values (solid line) are the sum of spectral contributions at .05, .06, .07, .08, .09, .10, .11, .12, .13 and .14 Hz. The dashed curve represents wave height generated by JONSWAP spectra as a function of fetch and wind in deep water.

The wind generation part of the model was again tested for 30 kt winds blowing over the same area. The significant wave heights computed by the model increase rapidly as the downwind fetch is longer. The model predicts a near fully arisen sea after only 50 nautical miles. The JONSWAP model predicts approximately linearly increasing wave height values for 30 kt winds until reaching fully arisen seas after 200 nautical miles of fetch. The large difference between the model calculations at 30 kts and the JONSWAP curves suggest the model over-builds seas for this wind speed and grid spacing.

The energy transport calculation in the model was found dependent on grid spacing and is invalid for large grid spaces and higher frequencies. Negative energies resulted for input at frequencies greater than .3 Hz with a grid spacing of 10 nautical miles. By decreasing $\Delta x = \Delta y$ to one nautical mile, the model can compute energy transport for .4 Hz and higher. A "fix up" in the program is made by setting any negative energy values to zero. The inability of the model to compute energy transformation for the short waves should be noted, even though this is the low energy side of the spectra.

B. NEARSHORE CIRCULATION ON A SLOPING BEACH

The nearshore current prediction part of the model was tested on a uniform sloping beach. Since the depth is uniform in the alongshore (Y) direction, the wave height, wave direction, current, wave set-up and surf should also be

The model was run for the same input with the flat bottom depth changed to 10 meters. The effect of friction only slightly reduced the fully arisen significant wave heights. However, the model generated fetch limited wave heights were approximately half a foot higher than the JONSWAP results. The increase in the height of the "shallow water waves" was probably a result of the change to a shallow water saturation spectrum. In shallow water the slope of the energy saturation spectrum with respect to frequency is -3 (Thornton, 1977). In deep water, the slope is -5 (Phillips, 1966). This results in relatively more wave energy at higher frequencies for the shallow water spectra.

To test the bottom friction in the model, a run was made with the same input as before except the depth was changed to 5 meters. The significant wave height curve shows a slow decrease after the first grid point. The model calculates larger frictional dissipation as the down grid distance increases. The model nearly reached a constant wave height, balancing generation and dissipation forces after 80 nautical miles. The values of predicted wave heights by the JONSWAP spectrum agree with the present model within 10 nautical miles, but tend to be larger for a longer fetch. For an open sea in a shallow region, the JONSWAP spectrum ignoring bottom friction effect gives a wave height four times larger than the predicted by the present model; this result emphasizes the importance of including bottom friction in shallow water wave models.

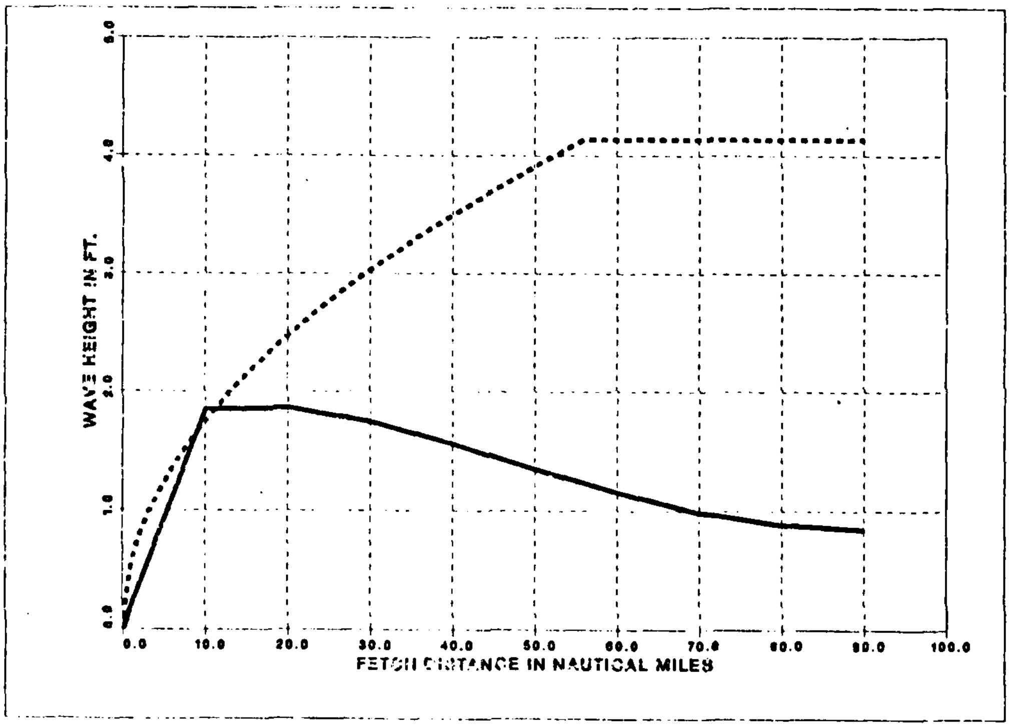

Figure 5. Significant wave height generated by a 15 kt wind in 5 meter depth. Model computed values (solid line) are the sum of spectral contributions at .05, .10, .15 and .20 Hz frequency bands. The dashed curve represents wave height generated by JONSWAP spectra as a function of fetch and wind in deep water.

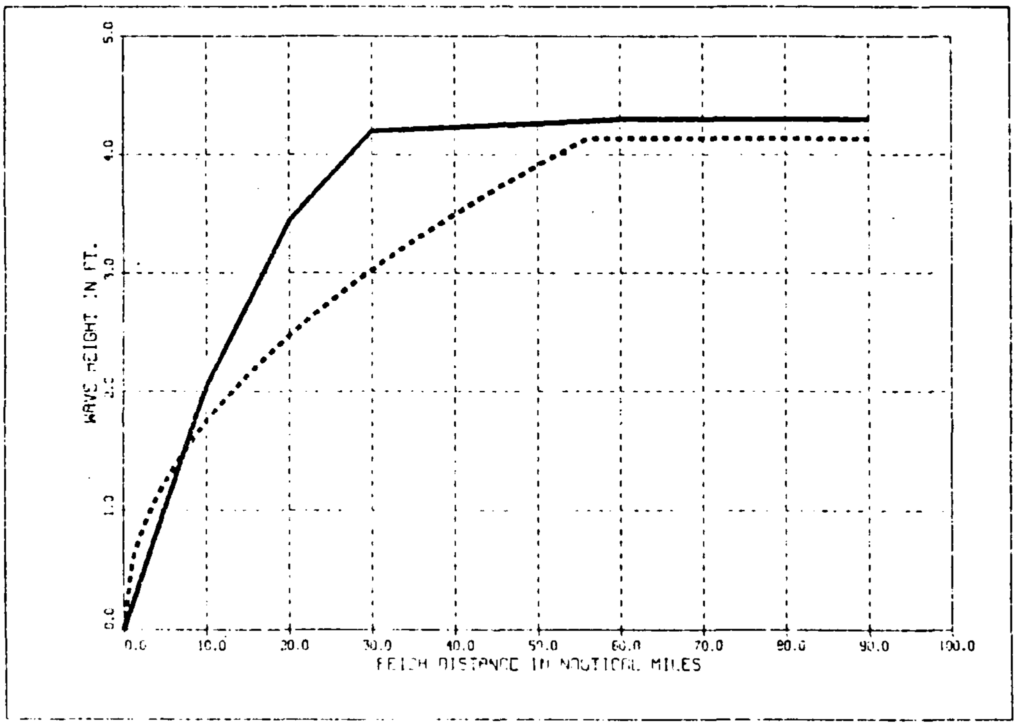

Fig. 4. Significant wave height generated by a 15 kt wing in 10 meter depth. Model computed values (solid line) are the sum of spectral contributions at .05, .10, .15 and .20 Hz frequency bands. The dashed curve represents wave height generated by JONSWAP spectra as a function of fetch and wind in deep water.

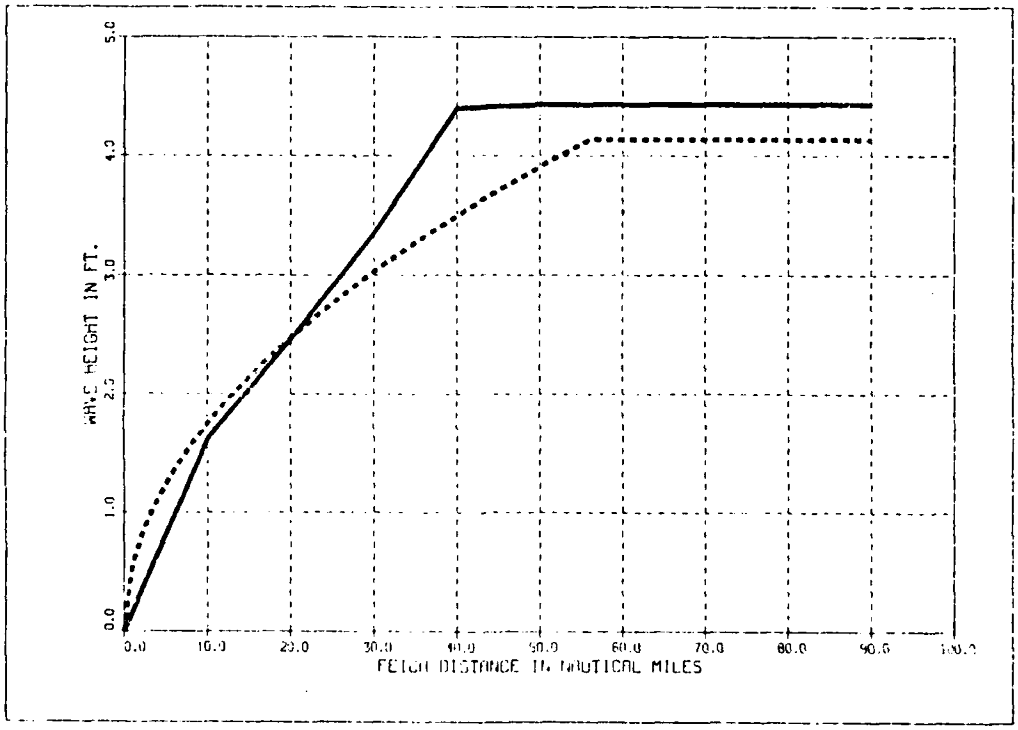

Figure 3. Significant wave height generated by a 15 kt wind in 100 m depth. Model computed values (solid line) are the sum of spectral contributions at .05, .10, .15 and .20 Hz frequency bands. The dashed curve represents wave height generated by the JONSWAP spectrum as a function of fetch and wind curves in deep water.

or breaker. The observation indicated two lines of breakers, the first near 60 meters and the second near 38 meters. The maximum measured wave height was .67 meters occurring 60 meters from the beach. The model forecast only one line of breakers .84 meters high and 16 meters from the beach.

The 5 February results (Fig. (11)) show the model almost forecast the surf height exactly at grid points. The model forecast one line of breakers 11 meters from the shore with a height of .61 meters. The observed breakers began about 39 meters from shore with a height of nearly .60 meters.

The model was also compared with surf zone observations from Torrey Pines State Beach, California for 4 and 10 November 1978 (Table I). The average angle was near normal to the shore. Fig. (12) shows the model input boundary wave on 4 November height was too small by about .05 meters (2 inches). This small error was due to interpolation between sensor locations. The model followed closely the observed wave heights between 160 and 240 meters, but it over-built the wave height inside 160 meters. The model placed the line of breakers 82 meters from shore with a height of .76 meters. Observed breakers were near 160 meters with a height of .48 meters.

The 10 November 1978 model of Torrey Pines was based on boundary conditions entered at 6.6 meters. Figure (13) shows uniform over-prediction of the wave height at grid points. The model forecast two lines of breakers, the first line 133

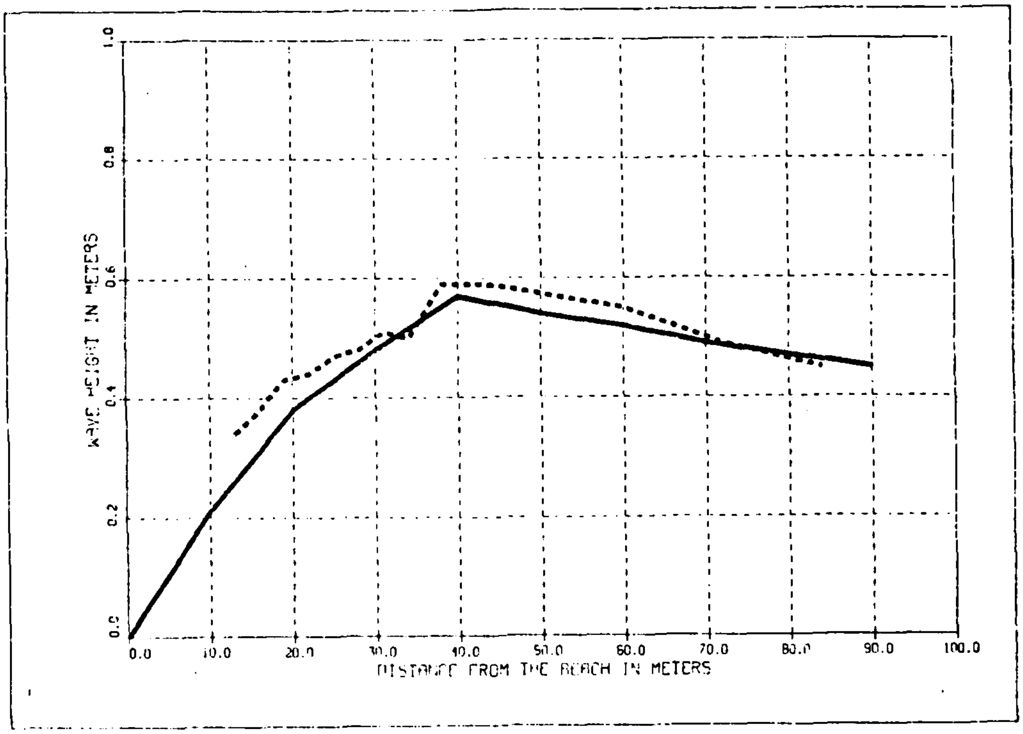

Figure 11. Santa Barbara surf zone wave height on 5 February 1980. Model computed values are represented by the solid line, observed heights are dashed.

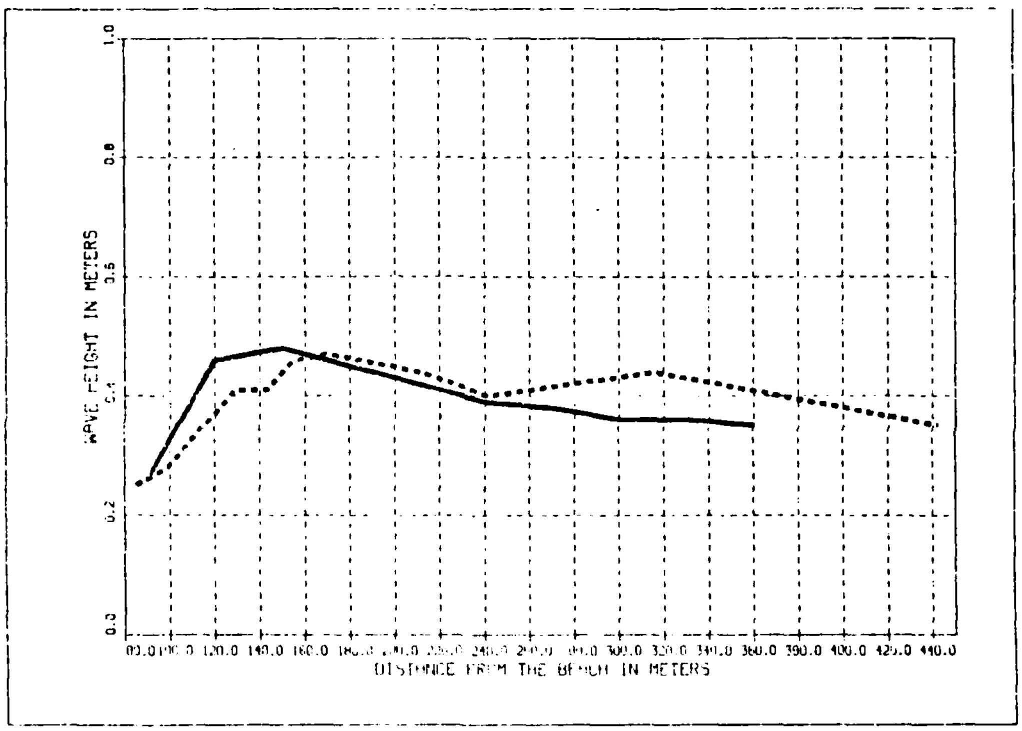

Figure 12. Torrey Pines surf zone wave height on 4 November 1979. Model computed values are represented by the solid line, observed heights are dashed.

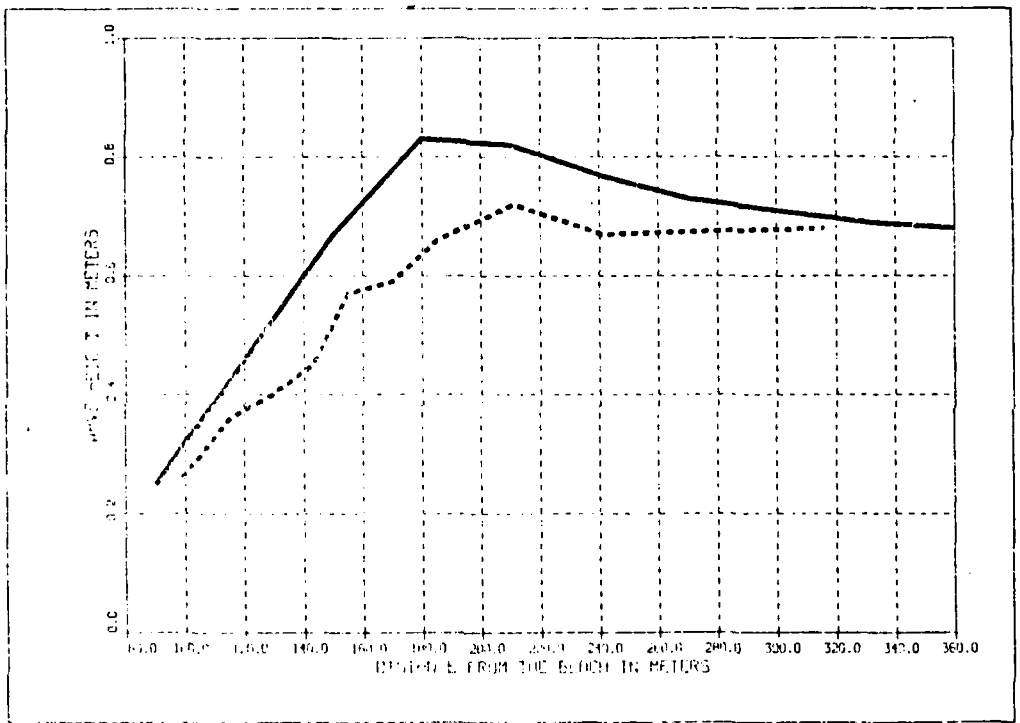

Figure 13. Torrey Pines surf zone wave height on 10 November 1979. Model computed values are represented by the solid line, observed heights are dashed.

meters from the beach with a height of 1.7 meters and the second 83 meters from the beach with a height of .75 meters. However, the observations showed no corresponding lines of breakers. The observed heights of the lines of breakers are .72 meters or less.

The wave height calculation by the model is, in general, close to the observed wave height. The surf zone width based on (26) is incorrect in every test run. The resulting calculations of breaker position, angle and height are dependent on the width of the surf zone and therefore these forecasts are incorrect.

VI. SUMMARY AND CONCLUSIONS

A. SUMMARY

A numerical model describing surface gravity wave transformation in shallow water region is written in BASIC for use on the HP-9845B. The original version of this model was based on the work by Wang and Chen (1983). The model consists of an open water wave program and a surf program. The open water model considers a wave energy spectrum generated by winds; the surf model predicts a shallow water wave field and the shear currents induced by wave breaking on an arbitrary bottom topography. The model is tested for cases of constant depth, a uniformly sloping beach and actual beaches. The application of the model to a field beach indicates the potential value for naval operational planning. Combinations of different conditions of wind, wave, and bottom bathymetry can be effectively simulated and serve as the basis for determining an amphibious landing.

The open water model is used to forecast sea heights over continental shelf and wide stretches of shallow water coast. The calculations of wave energy are the result of wind forcing, fetch distance, and bottom friction. The model predicts the spectral distribution of wave energy.

The surf model can predict wave shoaling, coastal currents and multiple breaker lines. In the model, the wave

heights and directions are calculated for a section of beach. The breaker heights, breaker types, and location of severe breakers are empirically determined based on the wave height calculations. This provides a map of the surf zone in two dimensions for Navy operations.

One of the drawbacks of this model is that the model is not programmed in an efficient manner. The wavenumber at a local water depth is calculated over a hundred times in nearly every subroutine for different frequency components. To allow for various options chosen and setting up the connectivity between subprograms, the integrated model was too large and not very well structured. Moreover, the unsteady approach to the steady state solution is time consuming and needs special care to avoid numerical instability. Using a steady state approach and reforming the program structure would facilitate the application of this model and improve the operational efficiency. Further modeling efforts should be directed toward this direction.

A problem in running the model is the choice of the energy bandwidth. The open water model uses energy spectra to describe the wave field. The selection of energy bands and bandwidths requires knowledge of wave spectra and gravity wave theory. The alternative to user choice is to have the model calculate energy contribution over the entire wave spectra. This would ensure all energy contributions across the spectra are considered. However, CPU time would increase to more than 6 hours if only 10 energy bands were used. (The Navy Spectral Ocean Wave Model uses 15 energy bands.)

B. CONCLUSIONS

This sea, surf and swell model at present is not suitable for operational use. The separate regimes, open water and nearshore current and surf, all have problems.

The open water part of the model requires sophisticated spectral energy input. The average Aerographer Mate does not have the knowledge to properly select input parameters. Only when the sea is dominated by a single narrow band swell with light wind is the wave energy input fairly easy (input wave height, direction and period). In addition, the open water model was shown to build up the sea height too fast for wind speeds of 30 kts raising doubt concerning the wind energy transfer part of the model.

The nearshore current part of the model is very slow to converge requiring more than 23 hours to complete the necessary 1000 iterations. The numerical scheme is therefore unsatisfactory for the HP-9845B computer. Recommendations include: 1) using a more stable scheme to increase the time step and reduce the number of iterations; 2) incorporate an implicit numerical scheme to calculate a direct solution of the currents such as in Wu and Liu (1985); or 3) use a simple one-dimensional current model implying a uniform beach alongshore.

The surf part of the model is probably the most "user friendly" and has the most potential. The surf part of the model is fast running and gives good solutions for grid point

wave heights. However, the width of the surf zone calculation is very poorly predicted. This error in turn causes the breaker line position, height and angle to be incorrect. The incorrect breaker predictions cause the effective surf calculation also to be invalid.

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